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RESEARCH PAPER

Spatial and environmental effects on plant communities in the Yellow River Delta, Eastern China

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Abstract: Types and structure of plant communities in the Yellow River Delta were investigated by using detrended canonical correspondence analyses (DCCAs) and a two-way indicator species analysis (TWINSPAN). The distribution pattern and influential factors of the plant communities were also analyzed by testing elevation, slope, soil characteristics, longitude and latitude of 134 vegetation samples collected by representative plot sampling methods. Results showed that all the 134 vegetation samples could be divided into seven vegetation groups, separately dominated by *Robinia pseucdoacacia, Imperata cylindrical, Miscanthus sacchariflеus, Suaeda salsa, Aeluropus sinensis, Phragmites australis* and *Tamarix chinensis*. The vegetation distribution pattern was mainly related to elevation, ground water depth and soil characteristics such as salinity and soluble potassium. Among the factors affecting distribution pattern of the plant communities, the species matrix explained by non-spatial environmental variation accounts for 45.2% of total variation. Spatial variation and spatial-structured environmental variation explain 11.8%, and 2.2%, respectively. Remained 40.8% of undetermined variation is attributed to biological and stochastic factors.

Keywords: detrended canonical correspondence analyses; environmental factors; plant communities; spatial factors; Yellow River Delta; two-way indicator species analysis

Introduction

Species composition and distribution of plant community are shaped not only by environmental conditions, but also by spatial factors, anthropogenic disturbance, and species competition etc. (Cousins and Eriksson 2002). In order to understand the relationship between the plant community and environmental factors, the potential importance of spatial factors, biotic interactions and other stochastic factors must be considered. Borcard et al. (1992) presented a quantitative statistical method for partitioning the variance in compositional data into independent components, using a series of (partial) canonical correspondence ordinations. This method allows to estimating the independent contributions of different variables, as well as the covariance between them, and it has been widely used to investigate the relationships between spatial and environmental components of compositional variation in a variety of research fields including palaeoecology (Ammann et al. 1993; Birks and Lotter 1994), biogeography (Ohmann and Spies 1998), and ecology (Borcard and Legendre 1994; Roche et al. 1998).

The Yellow River Delta is one of the most active regions of land-ocean interaction among the large river deltas in the world. The newly created wetland of the Yellow River Delta is a typical ecosystem of littoral wetland in estuary, which has rich wetland vegetation and hydrobios. The newly created wetland is also one of the most rapidly growing wetland ecosystems in estuary in the world. Vegetation in the newly created wetland is in the initial stage of plant community succession; therefore, the newly created wetland is very fragile (Yue et al. 2003). However, a considerable amount of oil and gas fields has been found in the Yellow River Delta. Meanwhile, since 1984, the population has been increasing at an annual growth rate of 10.5%. Unreasonable exploitation and use of natural resources have exerted serious pressures on vegetation in the newly created wetland.

The Yellow River Delta has aroused the interest of many researchers in different fields, such as the delta evolution (Pang et al. 2000; Xu 2002; Chang et al. 2004), flora (Shao et al. 2002), landscape change (Yue et al. 2003), and land use and land cover change (Wang et al. 2006). So far, few studies have ever been focused on the relationship between the vegetation and environmental factors. Wu (1994) and Wang et al. (2006) investigated the relationships between plant communities and soil characteris-

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tics in this region, but variation of plant communities was absolutely attributed to environmental factors. The contribution of spatial factors, biological factors and other stochastic factors were not concerned. To more clearly identify the effects of environmental, spatial and other factors on plant communities, a subsequent comparison is made in the present study following Borcard et al.'s (1992) method. Understanding relationships between environmental variables and vegetation distribution will help us to apply these findings to management, reclamation, and development of the Yellow River Delta.

Materials and methods

Study area

The Yellow River Delta is located in the northern part of Shandong Province, Eastern China (Fig. 1). It lies on the south side of the Bohai Sea, spanning from longitude 118°07′E to 119°18′E, and from latitude 36°55′N to 38°12′N. The natural conditions and geographical position make it a very distinctive region. As an active region, large amounts of sand is carried by the Yellow River and deposited at the river mouth to form new land. Within the delta, the underground water table is high and the water is saline. The entire area is covered mainly by wet and saline soil. The meadow, especially halophytic meadow, is the typical natural vegetation of the Yellow River Delta.

The region is characterized with temperate, semi-humid continental monsoon climate. Annual mean temperature ranges from 11.5°C to 12.48°C, with the warmest monthly temperature of 26.68°C in July and the coldest of 4.18°C in January. The annual rainfall is 590.9 mm and evaporation is over 1 500 mm. The monthly maximum rainfall is 227 mm in July and the minimum is 1.7 mm in January (Zang 1996).

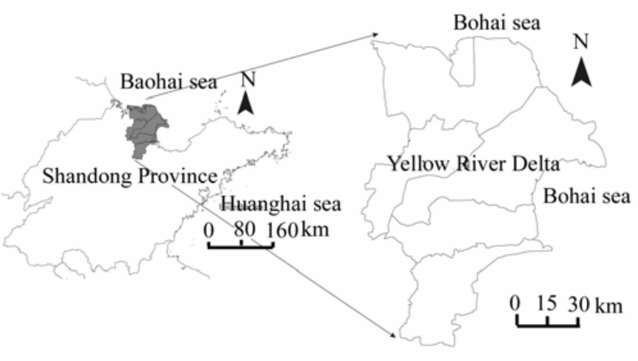

Fig. 1 Location of the Yellow River Delta

Vegetation sampling procedures

A quantitative survey of the vegetation was implemented in October of 2006 and 2007, and totally 134 samples were collected in this region. These samples were located at 200 m away from roads to eliminate the effect of disturbance caused by traffic. Representative plot sampling method was used and the size of samples was 20 m × 20 m for arbor species, 10 m ×10 m for shrub species, and 1 m × 1 m for herbaceous species. Floristic list, frequency, height, density, and canopy cover percentage were recorded using ordinal scale of Van der Marrel (1979). The importance value (IV) of each species in each sample was obtained by the sum for its relative density, frequency, coverage and height. Within each plot site, an investigation well was drilled to determine the ground water depth (GW). Geographical coordinates of samples were recorded using a GPS.

Soil sampling and data collection

Three soil samples (0–10, 10–20 and 20–30 cm) were collected at each site. These soil samples were air dried, thoroughly mixed and passed through a 2-mm sieve to remove gravel and boulders.

Measured soil factors included pH values (pH) in saturation extract, soluble sodium (SNa) and soluble potassium (SK), soil organic matter (SOM), total nitrogen (TN), and total phosphorus (TP). Soil pH was measured in soil extract (soil: water ratio 1:5); soluble sodium and potassium were measured with the flame photometry; soil organic matter was measured by the $K_2Cr_2O_7$ method; total nitrogen was measured with a Kjeltec System 1026 Distilling Unit (Tecator AB, Sweden); and total phosphorous was determined colorimetrically after wet digestion with H_2SO_4 plus $HClO_4$ (Liu 1996). To improve the precision of the results, three replicates were analyzed and averaged for each of the soil analyses.

Elevation of each sample was extracted from the 1:10000 digital elevation model, and slope inclination (Slope) of each sample was also calculated from the transformation of digital elevation model. The distance of each sample from the Yellow River (YRdis) and the coastline (Coadis) were calculated by spatial analysis to make sure whether the Yellow River and the sea have impacts on the distribution of the vegetation.

Vegetation classification and ordination

In order to reveal similarities and differences between plant communities and to obtain an effective analysis of the species and related environmental factors, both classification and ordination techniques were employed. Multivariate analyses were performed on the floristic data matrices, 134 samples and 29 species (134 × 29) where all species whose importance value was less than 5% were eliminated. A matrix of twelve environmental variables (134 × 12) was also made.

Classification of plant communities was achieved by a two-way indicator species analysis (TWINSPAN) (default settings; Hill 1979). The TWINSPAN groups were also subjected to an ANOVA based on soil variables to identify any significant variation between groups.

Relationships between species and environmental variables were analyzed using detrended canonical correspondence analysis (DCCA) (Ter Braak 1990). All the default settings were used for DCCA, and significance of species–environment correlation was tested by the distribution-free Monte Carlo test (1000 permutations). No samples were omitted from the analysis as outlier observations.

Partial detrended canonical correspondence ordinations

The partial detrended canonical correspondence ordination was made following Borcard et al. (1992). The variation of species abundance data was partitioned into independent components: (a) non-spatial environmental variation, (b) spatially structured environmental variation, (c) spatial species variation that is not shared by the environmental variables, and (d) unexplained variation and stochastic fluctuations.

Results

Vegetation groups in the Yellow River Delta

The dendrogram produced by TWINSPAN was inspected using the 29 species with importance value (IV) more than 5%. The sample sites were clustered into 19 clusters, and then those clusters were divided into seven groups (labeled A–G).

Group A (Form. *Robinia pseucdoacacia*) is arboreal forest. The understory is generally sparse, with occasional *Ophiopogon japonicus*, *Rubia cordifolia*, *Comnyza Canadensis* and *Setaria viridis*. Its canopy is 8–16 m high and the closure index is between 0.4 and 0.6. Group A is mostly distributed on the northern bank of the Yellow River and the east region of the old Yellow River course.

Group B (Form. *Miscanthus saccharifleus*). The main companions in Group B are *Artemisia princes*, *Suaeda salsa* and *Phragmites australis.* Its canopy is 0.6–2.4 m high, and the closure index is between 0.6 and 0.8.

Group C (Form. *S. salsa*). *S. salsa*, *Aeluropus sinensis* and *P. australis* are the characteristic species in group C. Its canopy is 0.1–0.4 m high, and the closure index is between 0.1 and 0.8.

Group D (Form. *A. sinensis*). *P. australis* and *Limonium bicolor* are main companions in Group D. Its canopy is 0.1–0.3 m high, and the closure index is between 0.15 and 0.6.

Group E (Form. *P. australis*). *S. salsa* and *A. sinensis, Sonchus brachyotus* and *Apocynum venetum* are main companions in group E. Its canopy is 0.3–1.8 m high, and the closure index is between 0.3 and 0.8. Group E is widely scattered in low-lying land along the Yellow River course.

Group F (Form. *Tamarix chinensis*). Companions in Group F are mainly *S. salsa*, *Apocynum venetum*, *Chenopodium album*, and *Artemisia capillaries*. Its canopy is 0.7–2.4 m high, and the closure index is between 0.3 and 0.8. Group F is the natural shrubbery on the seashore with a very large distribution area.

Group G (Form. *Imperata cylindrica*). Companions in Group G are *P. australis*, *Metaplexis japonica*, *Polygonum hydropiper*, *A. capillaris* and *S. brachyotus*. Its canopy is 0.2–0.6 m high, and the closure index is between 0.15 and 0.75.

Environmental characteristics of the seven vegetation groups

Different environmental variables (Table 1) showed that, Group A and B contained the more fertile samples that are indicated by high soil organic matter and total nitrogen contents, high ground water depth, slope inclination and elevation, and low salt content. In contrast, Group C, D, E, F and G contained less productive samples that are indicated by significantly low total potassium contents, lower ground water depth and nutrient values. In addition, salt and soluble sodium contents of Group G are lower than those of Group C, D, E and F.

Table 1. Environmental variables (Mean ± stand error) in different vegetation groups. Portioned seven groups were Group A (Form. *Robinia pseucdoacacia*), Group B (Form. *Miscanthus saccharifleus*), Group C (Form. *S. salsa*), Group D (Form. *A. sinensis*), Group E (Form. *P. australis*), Group F (Form. *Tamarix chinensis*), Group G (Form. *Imperata cylindrica*).

Groups	SOM ($g \cdot kg^{-1}$)	TN ($g \cdot kg^{-1}$)	TP ($g \cdot kg^{-1}$)	SK ($g \cdot kg^{-1}$)	SNa ($g \cdot kg^{-1}$)	pH	Salt ($g \cdot kg^{-1}$)	GW (m)	YRdis (km)	Coadis (km)	Elevation(m)	Slope(°)
Group A	17.0±1.1a	1.54±0.08a	0.75±0.05a	0.09±0.01a	0.53±0.1a	7.6±0.04a	2.2±0.39a	3.2±0.1a	32.2±1.9a	7.7±1.8a	4.9±0.51a	0.11±0.05a
Group B	14.8±3.2a	1.11±0.12b	0.59±0.02ab	0.04±0.01b	0.2±0.02b	7..8±0.04a	0.81±0.05b	0.78±0.03b	31.3±1.2a	8.7±0.9aa	2.5±0.14b	0.07±0.01a
Group C	7.8±0.6b	0.5±0.05b	0.67±0.01ab	0.12±0.02a	2.8±0.23ab	7.4±0.04a	11.0±0.9ab	0.69±0.12b	20.6±1.9b	11.4±1.2ab	1.6±0.15ab	0.04±0.01b
Group D	10.9±1.3ab	0.82±0.1ab	0.65±0.02ab	.0.05±0.01b	2.1±0.15ab	7.5±0.06a	8.7±0.6aa	0.47±0.04ab	14.3±3.3aa	17.1±3.2b	1.5±0.14ab	0.02±0.00b
Group E	11.8±1.5ab	0.83±0.11ab	0.65±0.1ab	0.07±0.01b	2.3±0.28ab	7.5±0.08a	9.4±1.1aa	0.59±0.11ab	19.7±2.7b	11.1±1.4ab	1.3±0.13ab	0.02±0.00b
Group F	7.2±0.4b	0.55±0.03b	0.66±0.13ab	0.09±0.01a	2.8±0.31ab	7.2±0.12a	11.2±1.3ab	1.2±0.15aa	23.5±1.4ab	9.2±0.98aa	1.9±0.22aa	0.06±0.01ab
Group G	7.1±0.4b	0.54±0.03b	0.61±0.03ab	0.05±0.01b	1.1±0.18aa	7.5±0.07a	4.2±0.7bb	0.85±0.13b	25.3±1.3ab	9.5±1.6aa	1.9±0.23aa	0.05±0.01ab
F	7.4	6.6	1.8	5.1	10.1	0.51	10	27	5.5	2.8	17.8	2.7
Sig.	0	0	0.038	0	0	0.08	0	0	0	0.013	0	0.018

Note: SOM, Soil organic matter; TN, Total nitrogen; TP, Total phosphor; SK, Soluble potassium; SNa, Soluble sodium; GW, Ground water; YRdis, Distance from the Yellow River Delta; Coadis, Distance from the Coastline. Different letters represent significant differences among the groups ($p < 0.05$, ANOVA LSD test)

Vegetation and environment ordination

In this study, the DCCA eigenvalues of the first two ordination axes explained 84.4% of the variance in the sample data. This means that the first two ordination axes are by far the most important for representing the variation of the seven vegetation types. Moreover, a Monte Carlo test confirmed the statistical significance of these two axes ($p = 0.01$).

Samples on the top of the ordination diagram (Fig. 2) belong to Group B, distinct for its high soil nutrient content and species composition. Samples spreading on the most positive axis 1 belong to Group A, and are typically high in total nitrogen, organic matter content. Samples spreading on the least positive axis 1 belong to Group C, and are typically high in salt and soluble sodium content. Samples distributed in the middle part of axis 1 are transition types belonging to Group D, G, E and F. Samples in the middle part of axes 1 and 2 are widely spread out and mostly overlapped.

It is noted that along axis 1, samples were associated significantly with elevation, slope and ground water depth. Axis 2 seems to represent essentially soluble potassium, soluble sodium and salt content (Fig. 2 and Table 2). This indicates that some environmental variables interrelates with physiognomy, such as groundwater depth, has great impact on the distribution of plant communities in the Yellow River Delta. Through a test for significance with an unrestricted Monte Carlo permutation test, the *F*-ratio for the eigenvalues of Axis 1 and the trace statistics were found to be significant ($p < 0.01$), indicating that observed patterns did not arise by chance.

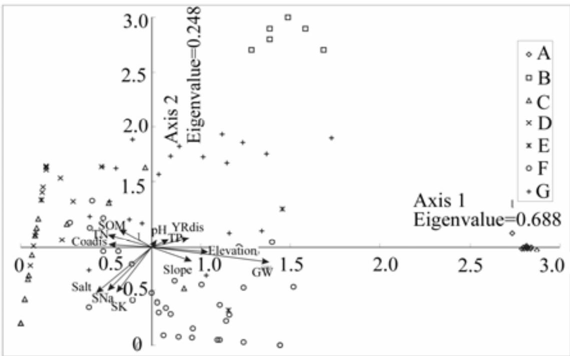

Fig. 2 Detrended canonical correspondence analysis (DCCA) ordinations of vegetation and environmental variables. The vectors represent environmental variables. The length of the vector is proportional to its importance and the angle between two vectors reflects the degree of correlation between environmental variables. The angle between a vector and each axis is related to its correlation with the axis.

Table 2. Intra-set correlations of environmental variables with the first two axes of detrended canonical correspondence analysis

Environmental variables	Axis 1	Axis 2
Soil Organic Matter	-0.206*	0.235**
Total Nitrogen	-0.202*	0.210*
Total Phosphor	-0.040	-0.210*
Soluble Potassium	-0.297**	-0.388**
Soluble Sodium	-0.397**	-0.472**
pH	0.0390	0.197*
Salt	-0.393**	-0.477**
Ground Water	0.752**	-0.125
Distance from the Yellow River	0.104	0.057
Distance from the coastline	-0.186**	0.110
Elevation	0.644**	-0.014
Slope	0.254**	-0.056

**p<0.01; *p<0.05

Correlation among environmental variables

Some of the environmental variables were found to be significantly correlated each other (Table 3). Among the 12 variables, elevation is significantly correlated with ground water depth and soil salt content. The ground water depth is negatively correlated with soluble sodium and salt content, and positively correlated with distance from the coastline, elevation and slope. Soil organic matter and total nitrogen content are positively correlated with ground water depth.

Controls of variation in plant communities

The relative importance of various processes that control variation of plant communities obtained by the partial detrended canonical correspondence ordination indicated that, environmental variables explained 45.2% of the variation in the species matrix, where 11.8% was predicted by the spatial factors of the plots. The species matrix explained by spatial structured environmental variation was 2.2%. The amount of unexplained species variation was 40.8%.

Table 3. Intra-set correlations between environmental variables

	SOM	TN	TP	SK	SNa	pH	Salt	GW	Yrdis	Coadis	Elevation
TN	0.65**	1									
TP	0.10	0.14	1								
SK	-0.07	-0.05	0.24*	1							
SNa	-0.15	-0.12	-0.06	0.47**	1						
pH	0.17	0.11	-0.31**	-0.38**	-0.21*	1					
Salt	-0.15	-0.12	-0.05	0.45**	0.98**	-0.22*	1				
GW	0.20*	0.19*	0.10	-0.16	-0.26**	0.03	-0.25**	1			
Yrdis	-0.10	-0.09	-0.04	-0.13	0.01	0.17	0.02	0.13	1		
Coadis	0.03	0.01	0.12	0.08	-0.18*	-0.21*	-0.19*	0.24*	-0.46**	1	
Elevation	0.06	0.05	0.09	-0.15	-0.36**	0.03	-0.38**	0.53**	0.21*	-0.05	1
Slope	0.02	0.04	0.03	-0.02	-0.13	-0.05	-0.17	0.22*	0.12	0.02	0.58**

Note: SOM, Soil Organic Matter; TN, Total Nitrogen; TP, Total Phosphor; SK, Soluble Potassium; SNa, Soluble Sodium; GW, Ground Water; YRdis, Distance from the Yellow River Delta; Coadis, Distance from the Coastline. **p<0.01; *p<0.05

Discussions

Classification of vegetation

Application of TWINSPAN technique in the present study has proved to be useful in classifying the samples into seven main vegetation groups that linked to geomorphology and the edaphic factors.

The Yellow River Delta is formed by the deposition of a large amount of sand and mud transported by the Yellow River. The downstream movement of freshwater combined with the inland movement of saline water from the ocean generates a salinity gradient in the estuarine systems (Yue et al. 2003). The salt content in soil of the newly deposited land is more than 3%, on which *S. salsa* are partially distributed. These *S. salsa* increase organic matter in the soil, which makes the area become *T. chinensis* or *A. sinensis* land. The secreting salt effects of *T. chinensis* and *A. sinensis* and accumulation of their dead branches and leaves resulted in the reduction of soil salt content and the increase in soil fertility, which makes the area evolved to *P. australis* or *M. saccharifleus* land. With gradual raise of terrain and drench of rainfall, the land is desalted and evolved to land suitable for forestry and agriculture (Tian et al. 1999). In other words, low-lying land along the Yellow River and its gullies has fully moisture content and damp soil, in which *P. australis* or *M. saccharifleus* is dominant species. The beach near the sea has a low and flat terrain subjected to erosion of the sea tide, in which soil salt content is higher than other lands and *S. salsa*, *A. sinensis* and *T. chinensis* are dominant. The higher land has a lower salt content, in which *I. cylindrica* is dominant. The area with soil salt content lower than 0.3% has partially become forestry lands such as *R. pseucdoacacia* (Yue et al. 2003).

Relationships between plant community and environmental variables

The results of DCCA ordination suggest that elevation, slope, ground water depth, and soil salt content have great impacts on the distribution of plant communities (Fig. 2 and Table 2). Ground water depth and soil salt content are also significantly correlated with elevation and slope (Table 4). This indicated that geomorphology is the key factor among the factors controlling species composition and distribution of plant communities. Geomorphology affects the ground water depth, relative humidity as well as temperature thus it is related indirectly to plant growth and distribution. In the Yellow River Delta, the ground water depth is very shallow due to the low elevation and short distance from the coastline, and the evaporation rate is high (Zang 1996). Therefore, salt accumulation close to the soil surface becomes a common phenomenon. Soil chemical parameters, such as soluble sodium, soluble potassium and soil salt content play an important role in controlling the distribution of the vegetation in this region.

According to Borcard et al.'s (1992) method, environmental variables explained 45.2% of the variation in the species matrix, where 11.8% was predicted by the spatial factors of the samples. The species matrix explained by spatial structured environmental variation was 2.2%. The amount of unexplained species variation was 40.8%. This suggests that the distribution of plant communities in the Yellow River Delta is mainly controlled by abiotic factors. However, other factors possibly related to disturbance or competition, not included in the analysis also strongly influence the species distribution. Therefore, examination of anthropogenic disturbance and other biotic effects could be important. This needs further research focusing on these variables and their role in determining composition of plant communities.

In addition, this study examined only one scale of variation in vegetation and environmental factors. Previous work has shown that at large scales, species abundance patterns can be attributed to habitat heterogeneity or environmental gradients, which fail to account for small-scale species interactions and the acquisition of resources (Currie 1991). Using different scales, factors dominating species composition could be different, because the resource variation is scale-dependent (Anderson et al. 2004), which may result in different species-environment relationships. More attention should be paid to the examination of scale in the future.

Conclusions

Application of both classification and ordination techniques has resulted in a clear demonstration of the vegetation pattern in the study area in quantitative terms. Assessing relationships between plant communities and environmental variables, spatial variables and biological factors, as was done in the current study, provides a broader framework for identifying important factors interrelated with vegetation than studies that focus on physical landscape variables alone.

Wetland ecosystem management must work with plant communities involving all of the interrelated biotic and abiotic influence. Understanding relationships between environmental variables and vegetation distribution in this area helps us to apply these findings to management of wetland ecosystems.

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